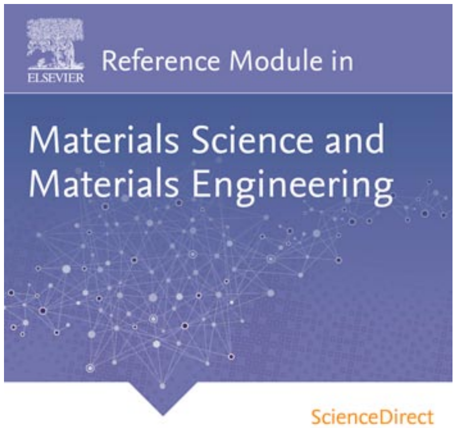

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Green Electronics☆

WS Young, IBM, San Jose, CA, USA
AA Abdullahi, University of Malaya, Kuala Lumpur, Malaysia, and Federal University of Technology, Minna, Niger State, Nigeria

1 Introduction

Green manufacturing (GM) is a manufacturing technique that minimizes toxic waste and pollution from both the raw material during production process and the product after manufacture. This target goal is achieved through manufacturing process and product design. According to Govindan *et al.* (2015) many green strategies were evolved and integrated in our real life operations and management. Likewise, the integration of green activities in manufacturing has emerged as an important research topic in recent years. More simply, green manufacturing includes environmental consciousness in manufacturing. Generally, the three 'R's (remanufacture, reduce, and reuse/recycle) are one main strategy of green manufacturing, which includes activities such as reducing hazardous waste volume, minimizing coolant consumption while machining, and calculating proper energy mixes to ensure a sustainable energy source (Dornfeld *et al.*, 2013; Govindan *et al.*, 2015). This concept of green manufacturing is extended to production of electrons products and even 'Toward green IT' (Zhang and Xie, 2015).

Electronic ceramics is a complex area for materials. They are usually a small part of a product that is not considered to be ceramic, usually involving several companies. One company makes the electronic ceramic starting with raw materials such as oxides. A second fabricates it into a ceramic component, for example, a capacitor or ceramic substrate, while a third integrates it onto an electronic subassembly such as a printed circuit board (PCB). Finally a fourth company inserts the subassembly in the final electronic product, for example, a television or personal computer – the item an end user recognizes. The fourth company may not even be familiar with the composition of the ceramic, knowing it merely as a sensor, capacitor, or disk drive head. In general, the latter two groups of companies see themselves as electronics companies, while the first two do not. Each company tends to work on environmental issues they control, unable to know/influence what the other companies do. Note there are companies, such as those making sonar for underwater applications that go from raw materials to the completed transducer encased in metal/plastic and protected by rubber. These are in the minority among electronic ceramics users.

The most economically important types of electronic ceramics include substrates, integrated circuit (IC) packages and multichip modules, capacitors, ferrites, insulators, piezoelectrics, and superconductors (World Electronics Development, 1998). Over 150 US companies produce or supply electronic ceramics. Insulators, substrates, IC packages, and capacitors represent about 80% of the total US market. Different varieties of the same product exist; capacitors can be single- or multilayer (MLC), the latter replacing single-layer capacitors during the 1990 s. MLCs can be leaded discrete parts or surface-mounted chips. The US market for electronic ceramics in 2001 is estimated to be just over US$6 billion (World Electronics Development, 1998).

In the US, The Green Electronics Council has also mentioned that there is a need to incorporate ability for direct communications between End-of-Life (EoL) managers and product designers in order to improve Design for EoL (DfEoL) process (Lee *et al.*, 2014) (Rifer *et al.*, 2009).

2 Being 'Green' and 'Greening' Products

'Green electronics' implies that more is done by a company environmentally than just concerning itself with emissions, water pollution, and other regulated areas. When looking for a 'green electronics' company, the first thing to look for is the corporate

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environmental policy, which sets the tone for how the company addresses environmental issues. A company registered for ISO 14000 has to have such a policy. As ISO 14000 becomes recognized around the world, more customers and regulatory agencies are accepting it as proof that the company is 'green.' Another 'green electronics' tool is the incorporation of DFE guidelines into product design. Some examples are:

- Reduced use of energy
- Minimum use of hazardous materials
- Reduced emissions during use
- Modular, interchangeable parts
- Designed for easy disassembly
- Reusable/recyclable components
- Marked plastics – a minimum of different types
- Recycled feedstock in plastic parts
- Use of 'clean' manufacturing processes
- Hazardous waste minimized
- 'Clean' packaging and product take-back

3 'Greening' Processes

The following areas of manufacturing and assembly processes *always* need to be included in the environmental activities of a 'green' company:

- conserving water and treating wastewater – elements/metals, specific, and total organics;
- choosing 'benign' solvents and minimizing the amount used;
- air emissions – particulate, vapors, gases, and even heat;
- dust – minimization, collection, disposal/recycle; and
- protecting employees – inhalation, ingestion, dermal contact.

Specific ceramic processes have their own environmental focus areas:

- Powder processing. Handling of fine powders; toxic solvent use/disposal; hoods, gloveboxes, and personal protective equipment (PPE); minimizing waste; recycling; air emissions and dust control.
- Prefiring processes. Minimizing drying; 'benign' slurries, binders, electrolytes, and precursors; aqueous vs. organic solvent systems; form-to-size; sol–gel chemicals.
- Thermal treatment/firing. 'Safe' atmospheres, stack emissions; 'benign' additives (gases); energy/fuel usage; thermal design; binder burnout/firing optimization.
- Postfiring processing. Use and disposal of 'benign' lapping slurries, grinding coolants, etc; plating/etching bath replenishment and recycling.
- Assembly processes. Soldering operations; 'benign' encapsulants and epoxies; emissions.
- Cleaning processes. Aqueous vs. solvent-based; spray vs. bath; additives, surfactants; pH dependency; foam control; recycling/reuse/treatment of liquids.

Conservation of raw materials pays for itself both in cost and environmental improvement. The amount of tantalum powder required per million surface-mounted capacitors was reduced from 400 lb (180 kg) in 1982 to roughly 100 lb (45 kg) in 1996 (Electronic Buyers' News, 1996). This also translates to less waste being generated. It is much better to minimize material usage 'up-front' than to dispose of it later.

4 New 'Greener' Processes

With increased microminiaturization of electronics, new processes have emerged that are more environmentally 'benign' than former processes. These include thin-film processes like sputtering, chemical vapor deposition, and ion etching that replace thick-film or mechanical processes, the use of surface-mounted components instead of discrete components, water-based slurries replacing solvent-based ones, etc. Vacuum processes can be quite complicated such as plasma-enhanced metalorganic chemical vapor deposition (PE-MOCVD) (Dey, 1996; Dey and Alluri, 1996; Petuskey *et al.*, 1992) or reactive ion etching (RIE). They tend to replace 'wet' processes and involve safe handling/disposal of small quantities of gases used in the vacuum chamber instead of large quantities of wastewater, solvents, acids, etc., used by wet processes. Note that some of the gases used for thin films are more toxic than the liquids used in most wet processes, even in small quantities. Proper gas handling techniques, such as double piping and plasma decomposition of exhaust gases, are required to make the processes safe and environmentally noncontaminating.

Replacing thick-film coatings with thin films on disk drive substrates reduces hazardous waste by over 80% in one disk manufacturing process. Thin films have been successfully used in such products as transducers, thermistors, electrooptics, microelectronics packaging, microactuators/microsensors, ferroelectric memories, ULSI DRAMs, and digital receivers. It is even possible to synthesize the material in the thin film during deposition, at a lower temperature than powder calcining. Petuskey *et al.* (1992) have synthesized Pb–Zr–Ti oxide thin films below 500 °C and Sr–Ti–O films below 400 °C using electron cyclotron resonance MOCVD (ECR-MOCVD) (Alluri *et al.*, 1998).

5 'Greening' Energy Use

With ceramics, large quantities of energy are generally required during fabrication, making energy consumption an important environmental aspect. Whittemore (1999) has studied the energy used in preparing many types of ceramics. For barium titantate only 2% of the furnace energy is required to heat the powders and react them. The rest goes into process and atmosphere control that is required by many electronic ceramics whose properties are composition sensitive. Nevertheless, ceramic firing is not the major energy usage over the life of most electronic ceramic materials – end use of the final product is. Lippke (1994) states: "Customer use is also the major contributor to smog, nitrogen oxides, acid rain, and carbon dioxide release – all stemming from a product's energy consumption." A US$10, 110 V electronic clock consumes nearly US$10 in electricity over 10 years. He calculates that 31% of electrical waste comes from commercial/industrial electrical products, 29% from appliances, 14% from batteries, 8% each from consumer electronics and cable, and 3% each from office computers and lighting fixtures.

'Green' electronic ceramics have been instrumental in decreasing the amount of energy required in building or using many products. The storage capacity of 3.5 in./2.5 in. disk drives doubles roughly annually, allowing the same energy to store twice the data in the new drive. Smaller magnetoresistive ceramic heads and glass disk substrates drive this rapid evolution in technology. The switch from discrete capacitors to surface-mountable MLCs has increased PCB densities, allowing the same amount of raw board stock to become more finished products and decreasing the amount of energy used per finished item. There are many other similar examples.

6 'Greening' Worldwide

Much of the processing and assembly of electronic ceramics are done in areas of the world with very low labor costs. This includes the four types of companies identified in Section 1. These companies make most consumer products, PCBs, and virtually anything with discrete, leaded components. A 'green' company with plants all over the world uses the same environmental controls everywhere, making the most stringent regulation a *de facto* worldwide standard. It also requires vendors and suppliers to do the same. This pressures smaller electronics companies working for large 'green' ones to also be environmentally conscious.

7 Banned/Restricted Materials

Chemicals and materials are being banned or restricted in various places around the world, which affects electronic products. In Japan, the Specific Household Appliance Recycling Bill (SHARB) is scheduled to take effect in 2001. It focuses on lead in landfills and regulates disposal of television sets, refrigerators, air conditioners, and washing machines and will be likely to include personal computers. As a result, there is intense development of lead-free solder for electronics (Abtew and Selvaduray, 1998).

In Europe, the Directives on Waste Electrical and Electronic Equipment (WEEE and EEE) are scheduled to be implemented in 2008. EEE phases out the use of lead, mercury, cadmium, chromium(VI), and halogenated flame retardants in electronic equipment. WEEE requires product take-back by manufacturers at the end of the life of the product. The final laws may not completely ban lead in solder, but will affect how future electronic products are built and marketed worldwide.

There are lists of banned/regulated materials in various countries that affect purchasing decisions. One of these is 4E (CEFIC–EACEM–ECTEL–EECA–EUROBIT), 'Excerpt of restrictions on substances from legal provisions for special application in electric and electronic products,' from EMEA (Europe/Middle East/Africa) dated June 18, 1998 (European Association of Manufactures of Business Machines, 1998). It restricts the use of the following materials, usually above a limited amount (0.001–1.0 wt.%): aliphatic CHCs (eight solvents like chloroform); arsenic compounds in antifouling paints; asbestos; azo colorants with 20 carcinogenic amines; lead batteries and three lead compounds in paint; cadmium and its compounds in plastics, paints, etc.; 25 chlorinated dioxins and furans; 13 chlorofluorocarbons (CFCs) and halons; formaldehyde in wood/cleaning agents; pentachlorophenol (PCP) and its salts; organostannic compounds in paints; polychlorinated biphenyls (PCBs) and terphenyls; mercury compounds in paints, wood, and textiles; mercury in batteries; creosotes in wood; lead, cadmium, mercury, and hexavalent chromium in packaging; and acrylonitrile, butadiene, and vinyl chloride for plastics used with foodstuffs. The USA bans eight additional CFCs, plus Halon-2402 and methyl bromide not on the June 1998 4E list.

There is also a second part to the 4E list, a 'list of substances to be avoided,' including: antimony and its compounds; arsenic and its compounds; azo dyes; beryllium and its compounds; brominated biphenyls, etc.; cadmium and its compounds; chlorinated hydrocarbons; chromium(VI) compounds; epichlorohydrin (used in some epoxies); HCFCs; artificial mineral fibers < 3 μm; mercury and its compounds; radioactive substances; selenium and its compounds; and vinyl chloride (monomer) > 10 ppm.

'Green' electronics manufacturers use such lists to generate an internal materials specification for their products, often labeling it a 'vendor materials spec' used for purchased components, as illustrated above. Such specifications are a necessary part of the 'greening' process.

Schwartz *et al.* (1997) have noted that Europe and Japan are leading the effort to control materials in 'green' electronics: "There is a growing awareness of environmental and energy-related issues pertaining to electronic ceramics in Japan, but not necessarily in the United States … New environmental regulations may result in the limited use of current materials – e.g., lead-based relaxor dielectrics – and development of alternative materials – e.g., lead-free piezoelectrics and lead-free solders."

8 Lead – An Example

No other material as important to electronics is under the intense worldwide environmental scrutiny as is lead, found in a surprising number of electronic components. It is found in virtually all electronic solders, as well as many alloys (brass, bronze, beryllium copper, nickel silver alloys, and hot/cold rolled zinc). Most piezoelectric and ferroelectric ceramics derive their behavior from the lead compounds they contain (Nordyke, 1984, pp. 106–108). Lead zirconate titanate (PZT) is a good example of a lead-containing piezoelectric/ferroelectric ceramic. The best emergency backup batteries available are rechargeable sealed lead–acid storage batteries. Lead can stabilize poly(vinyl chloride) (PVC) to prevent degradation of electrical and physical properties by heat and light. According to Nordyke (1984, p. 197): "Of the known vinyl stabilizers, only compounds of mercury, silver, and lead form chloride salts which are essentially insoluble in water." Because lead is the principal environmental focus material in the electronics industry, we will use it as an illustration.

There is good reason to be careful in the use of lead, especially around children. Many studies show that increased lead in their blood causes loss of learning ability and other physical problems (Lead Industry Association, 1999). According to Nordyke (1984, pp. 159, 160): " … Lead exposure has been a prime focus of the media and of governmental regulatory agencies. The result has been that lead has become one of the most studied, regulated, and, when properly handled, safe materials known to man." He notes that lead poisoning is not a significant hazard in the lead mining industry, which it would be if just having lead-containing materials present raised blood lead levels (Nordyke, 1984, p. 196). Children tend to get lead poisoning by chewing on lead-based paint, a material common up to the 1970s but now banned. In the ceramic industry, much of the danger from lead comes from the breathable dust created by transporting, mixing, and handling soluble inorganic lead compounds (Nordyke, 1984, pp. 159, 160) and disposal of lead-containing waste materials (Nair *et al.*, 1996). Dust control is a major effort in this area of the ceramics industry. Lead vapors from smelting/firing can also be absorbed into the body, so control of stack emissions is a major environmental requirement for primary lead smelters, lead recyclers, companies making PZT, etc. The US EPA has set a primary drinking water standard of 15 ppb for lead, requiring more and more municipal sewer plants to monitor lead in incoming wastewater from manufacturing companies.

One of the environmental success stories among industrialized nations is the decrease in lead blood levels after discontinuing the use of tetraethyl lead in automobile fuel. Lead reductions of up to 90% were seen in both blood and air testing.

To minimize the loss of lead in piezoelectric/ferroelectric materials such as PZT, they are often fired in closed crucibles with excess lead. After firing, the lead is bound in a very stable structure, making the material resistant to liquids, temperature, and decomposition. According to Nair *et al.* (1996): "Lead-based electroceramics – including lead titanate, lead zirconium titanate, lead lanthanum zirconium titanate and lead magnesium niobate – are water insoluble … Lead-based electroceramics and glasses should not be placed in the hazardous materials category with [soluble] inorganic lead compounds, but the regulation of material supply, production and disposal is desirable."

Eliminating lead use in one area can actually increase its effect in another. A *Lifecycle analysis* (LCA) on solder by Allenby (1992) illustrates this. The best candidates to replace lead in solder are indium, bismuth, and silver-filled conductive epoxy, all less toxic than lead. However, the analysis concluded that lead is preferable, primarily because the other three elements are found only in low concentrations, usually as by-products of lead, copper, and zinc mining/refining. Replacing a pound of lead in solder with either bismuth or indium would require mining tons of lead ore. Banning lead in solder would also cause shortages of both elements because lead usage in solder exceeds the known world reserves of both bismuth and indium (Allenby *et al.*, 1992).

Because of this, the newest solder replacements (2000) include tin–copper and tin–copper–silver alloys.

Lead must be controlled to fabricate more environmentally friendly PCBs. It has been reported that the primary hazardous waste flows in PCB assembly operations are solder paste (solid, airborne particulates, and wastewater), solder dross, solvents, and volatile organic compounds (VOCs) from soldering and wastewater (Siddhaye and Sheng, 1997; Worhach and Sheng, 1997). 'Green' companies capture the solvents and VOCs in air abatement devices to be disposed of as hazardous wastes. The waste solder paste and dross are recycled. Wastewater is minimized and treated. The amount of air emissions generated in fabrication and assembly of PCBs has decreased with use of water-based/low-solvent processes, such as water-soluble solder flux.

The newer technologies discussed above help minimize the environmental effects of lead-based ferroelectrics and other heavy metal oxides. Dey (1992) has demonstrated that integrated lead–perovskite thin-film dielectrics are possible, and Barz *et al.* (1998) have shown that the composition of SrBiTa oxide thin films can be carefully controlled using sol–gels. The advantages of these new technologies include the generation of very little waste. The small amount of residual gases coming from the vacuum pumps does have to be characterized and properly treated, if necessary.

9 'Greening' – Where to Start

The basic principles underlying 'green electronics' can be found in various sources (Office of Technology Assessment, 1992; Graedel and Allenby, 1995; Young, 1997). The IEEE 'International Symposium on Electronics and the Environment' highlights 'green' electronics annually. Use of some 'green electronic principles' helps to keep things in perspective:

- Green electronics starts at the top of a company
- Educate everyone in the company
- Measure your green progress
- Build a company green team
- Pick the low-hanging fruit first
- Make your efforts public
- Use serendipity – if technology becomes greener on its own, count it
- Assume green dividends will exceed the costs over time
- Use outside partnerships and alliances
- Conclusions will evolve – today's best is not tomorrow's.

In the future, 'green' electronic companies will focus more on preventing pollution rather than treating it. Wasa (1995) suggests: "Total system energy consumption should be counted to evaluate the environmental load … Present global environmental issues will be solved by resourceful energy technology and waste management under a minimum pollution of environment [*sic*]." His suggestions for electronics materials include green sheet MLC sintering of $PbO/SiO_2/B_2O_3/Al_2O_3/BaTiO_3/RuO_2$ at 900 °C (suggested by Newnham), SiC synthesized below 500 °C (Wasa), and ZnO single crystals as low as 100 °C (Mitsuyu).

Much 'green' progress has been made, but there are still many electronic ceramic environmental issues to be addressed. Many of the best solutions will be superseded by new knowledge and methods (the last 'green electronic principle' listed above). Being 'green' is not a one-time effort, to be completed and forgotten about. It is a methodical, long-term effort that improves with time. It becomes an integral part of how a company looks at itself, what it sells, how it does business, and how it interacts with its neighbors. It will be a necessary part of doing business in the future. Consumers and government alike will require it.

References

Abtew, M., Selvaduray, G., 1998. Lead-free solders for surface mount technology applications. Chip Scale Review 29–40.
Allenby, B.R., 1992. Design for environment: Implementing industrial ecology. Ph.D. dissertation, Rutgers University.
Allenby, B.R., *et al.*, 1992. An assessment of the use of lead in electronic assembly. Proceedings of Surface Mount International 1992 1–28, San Jose, CA.
Alluri, P., Majhi, P., Tang, D., Dey, S.K., 1998. ECR-MOCVD of the Ba–Sr–Ti–O system below 400 °C. 1. Processing Integrated Ferroelectrics 21, 305–318.
Barz, R., Amrhein, F., Shiu, Y.-W., Dey, S.K., 1998. Processing and effects of annealing in sol–gel derived $SrBi_2Ta_2O_9$ thin films. Integrated Ferroelectrics 22, 65–74.
Dey, S.K., 1992. Integrated Pb–perovskite dielectrics for science and technology. Ferroelectrics 135 (1–4), 117–130.
Dey, S.K., 1996. Sol–gel science and PE-MOCVD of dielectric perovskite films in ferroelectric thin films: synthesis and basic properties. In: Paz de Araujo, C., Scott, J.F., Taylor, G.W. (Eds.), Ferroelectrics and Related Phenomena. The Netherlands: Gordon and Breach, pp. 329–389.
Dey, S.K., Alluri, P., 1996. PE-MOCVD of dielectric thin films: Challenges and opportunities. Materials Research Society Bulletin 21 (6), 44–48.
Dornfeld, D., Yuan, C., Diaz, N., Zhang, T., Vijayaraghavan, A., 2013. Introduction to Green manufacturing Green Manufacturing. US: Springer. pp. 1–23.
Electronic Buyers' News, August 27, 1996.
European Association of Manufacturers of Business Machines, 1998. European Association of Manufacturers of Business Machines Eurobit Position Papers. Available from: http://www.fvit-eurobit.de/pages/defposeu.htm (accessed 03.09.15).
Govindan, K., Diabat, A., Madan Shankar, K., 2015. Analyzing the drivers of green manufacturing with fuzzy approach. Journal of Cleaner Production 96, 182–193.
Graedel, T.E., Allenby, B.R., 1995. Industrial Ecology and the Automobile. New York: Prentice-Hall.
Lead Industry Association , 1999. http://www.leadinfo.com/HEALTH/childexp.html (accessed 03.09.15).
Lee, H.M., Lu, W.F., Song, B., 2014. A framework for assessing product end-of-life performance: Reviewing the state of the art and proposing an innovative approach using an end-of-life index. Journal of Cleaner Production 66, 355–371.
Lippke, J., 1994. Green strategies cope with electronic product energy and end of life EDN. 119–126.
Nair, N., Bhalla, A., Roy, R., 1996. Inorganic lead compounds in electroceramics and glasses. Ceramic Bulletin 75, 77–82.
Nordyke, J.S., 1984. Lead in the World of Ceramics. American Ceramic Society 106–108.
Office of Technology Assessment Green Products by Design: Choices for a Cleaner Environment, 1992. OTA-E-541.
Petuskey, W.T., Richardson, K., Dey, S.K., 1992. Chemical aspects of Pb–Zr–Ti oxide thin film synthesis by PE-MOCVD below 500 °C. Integrated Ferroelectrics 2, 1–4.
Rifer, W., Brody-Heine, P., Peters, A., Linnell, J., 2009. Closing the loop electronics design to enhance reuse/recycling value. Green Electronics Council, January, pp. 1–35.
Schwartz, S.L., Shrout, T.R., Takenaka, T., 1997. Electronic ceramics R&D in the US, Japan: II. Japanese view. Ceramic Bulletin 78, 51–55.

Siddhaye, S., Sheng, P., 1997. Integration of environmental factors for process modeling of printed circuit board fabrication. Proceedings of IEEE International Symposium on Electronics and the Environment, 226, San Francisco, 33.
Wasa, K., 1995. Materials engineering for a better global environment. Bulletin of Materials Science 18, 937–953.
Whittemore, O.J., 1999. Energy use and efficiencies in firing ceramics, melting glass. Ceramic Bulletin 78, 69–71.
Worhach, P., Sheng, P., 1997. Integration of environmental factors in process modeling for printed circuit board manufacturing: I. Assembly. Proceedings of IEEE International Symposium on Electronics and the Environment, San Francisco, CA, pp. 218–225.
World Electronics Development No. 4 1998, Cornhill, London
Young, W.S., 1997. Greenhorn engineering: how to avoid environmental quicksand and other mistakes. Ceramic Bulletin 76, 57–63.
Zhang, N., Xie, H., 2015. Toward green it: Modeling sustainable production characteristics for Chinese electronic information industry, 1980–2012. Technological Forecasting and Social Change 96, 62–70.

Further Reading

IEEE International Symposium on Electronics and the Environment. Proceedings published yearly by IEEE/ISEE, Piscataway, NJ.